Procedural Volumetric Cloud Modeling, Animation, and Real-time Techniques

David S. Ebert

School of Electrical and Computer Engineering

Purdue University

ebertd@purdue.edu

Overview

- *Proceduralism*
- *Background*
- *Modeling Gases*

Overview

- Cloud Modeling
- Examples Using Commercial Systems
- Hardware Issues and Real-Time Gases
- Conclusion
- Future Directions for Research

Proceduralism: Advantages of Procedural Techniques

Flexibility

Parametric Control

Data Amplification

Procedural Abstraction - High Level Control

Complexity on Demand

- Inherently multi-resolution model
- Computational savings
- Ease of anti-aliasing

Background

Why Model Gases ?

Important Visual Characteristics

Rendering System Considerations

Why Model Gases ?

Visual Realism

Artistic Effects

Important Visual Characteristics

- *Amorphous*
- *Swirling*
- *Attenuation of Light*
- *Shadowing*
- *Illumination*

Example: Fog

Rendering System Considerations:

Issues

Volume Rendering Support

Illumination Issues

- Participating media - scatters, reflects, absorbs light
- Low-albedo models (single scattering)
- High-albedo models (multiple scattering)

Volume Shadowing

Modeling Capability

My System

Scanline A-buffer w/ Volume Tracing

Low-albedo Illumination Model

3D Table-based Shadowing

- Fast, efficient
- 10 to 15 times faster than ray-traced shadows

Procedural Volume Density Functions

Modeling Gases: Previous Approaches

Surface Approaches

- Hollow/flat objects
- Interaction problems
- Fast

Volume Approaches

- Greater realism, flexibility
- Slower

Volumetric Modeling Advantages

- *Accurate Shadowing*
- *Realistic Illumination*
- *Realistic Simulation of Natural Volumetric Phenomena (Clouds, Gases, Water, Fire)*

Volumetric Procedural Modeling (VPM)

Basic VPM Primitives

- Any function of three-dimensions
- Stochastic:
  - *Noise, turbulence, fBm*
- Regular: implicit functions
  - *Smooth blending*
  - *Useful primitives (spheres, cylinders, ellipsoids, skeletons)*

Volumetric Procedural Gas Modeling

Turbulence-based Procedures

- Perlin’s noise and turbulence functions

Shape Resulting Gas

- Simple mathematical functions

Defines Volume Density

Basic Gas Procedure

Density =

$$(\mathit{turbulence}(\mathit{pnt}) * \mathit{density\_scaling})^{\mathit{exponent}}$$

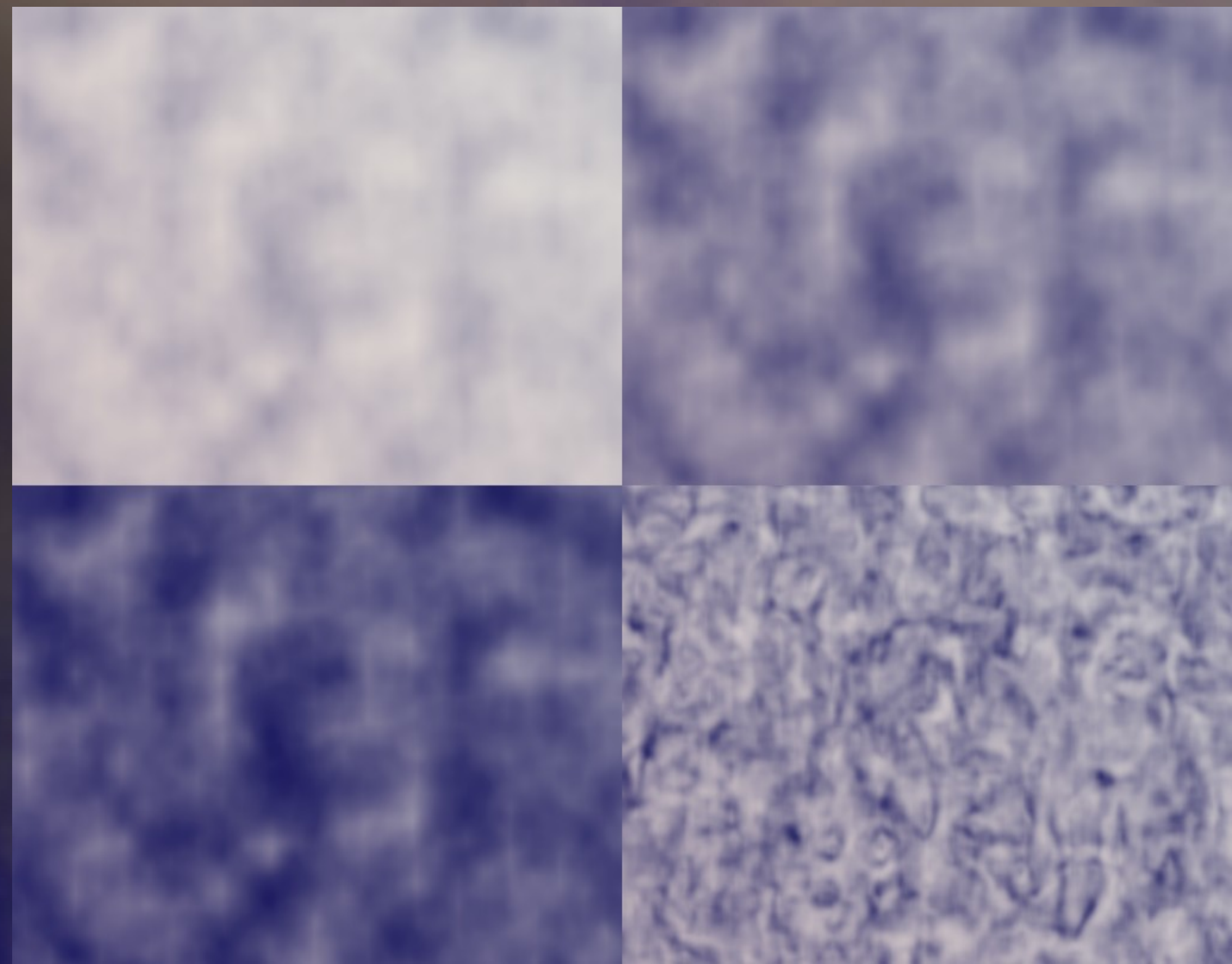
- Exponent typically 1.0 to 10.0

Gas Shaping Primitives

Power Function

Sine Function

Exponential Function



Steam Rising From a Teacup

- *Volume of Gas Over the Teacup*
- *Basic Gas Procedure Used for Density*

Steam Rising …

Shape Gas Spherically

Shape Gas Vertically

Volumetric Cloud Modeling: Volumetric Procedural Implicits

Previous Volumetric Procedural Implicit Modeling

- Perlin: hypertextures
- Stam: fire modeling, clouds
- Kisacikoglu: gas plasma - Sphere

Previous Cloud Modeling

- Surface-based (Gardner)
- Fractal-based (Voss)
- Volume-based (Kajiya, Stam)

Volumetric Procedural Implicit Modeling

Two Tiered Approach

- Cloud macrostructure
  - *Volumetrically rendered implicit primitives*
- Cloud microstructure
  - *Procedurally defined natural detail*
  - *Procedural volumetric density functions*

Cloud Macrostructure

Primitive-Based Implicit Models

- Currently: spheres, cylinders, ellipsoids
- Wyvill’s blending function

Ease of Specification, Animation, Global Deformation

- Easily controlled by particle system dynamics

Example Implicit Cloud

Cloud Microstructure

Volumetric Procedural Model

Built-in Multiresolution Model

Features:

- Main primitives: noise and turbulence
- Mathematical functions for shaping
- Natural controls

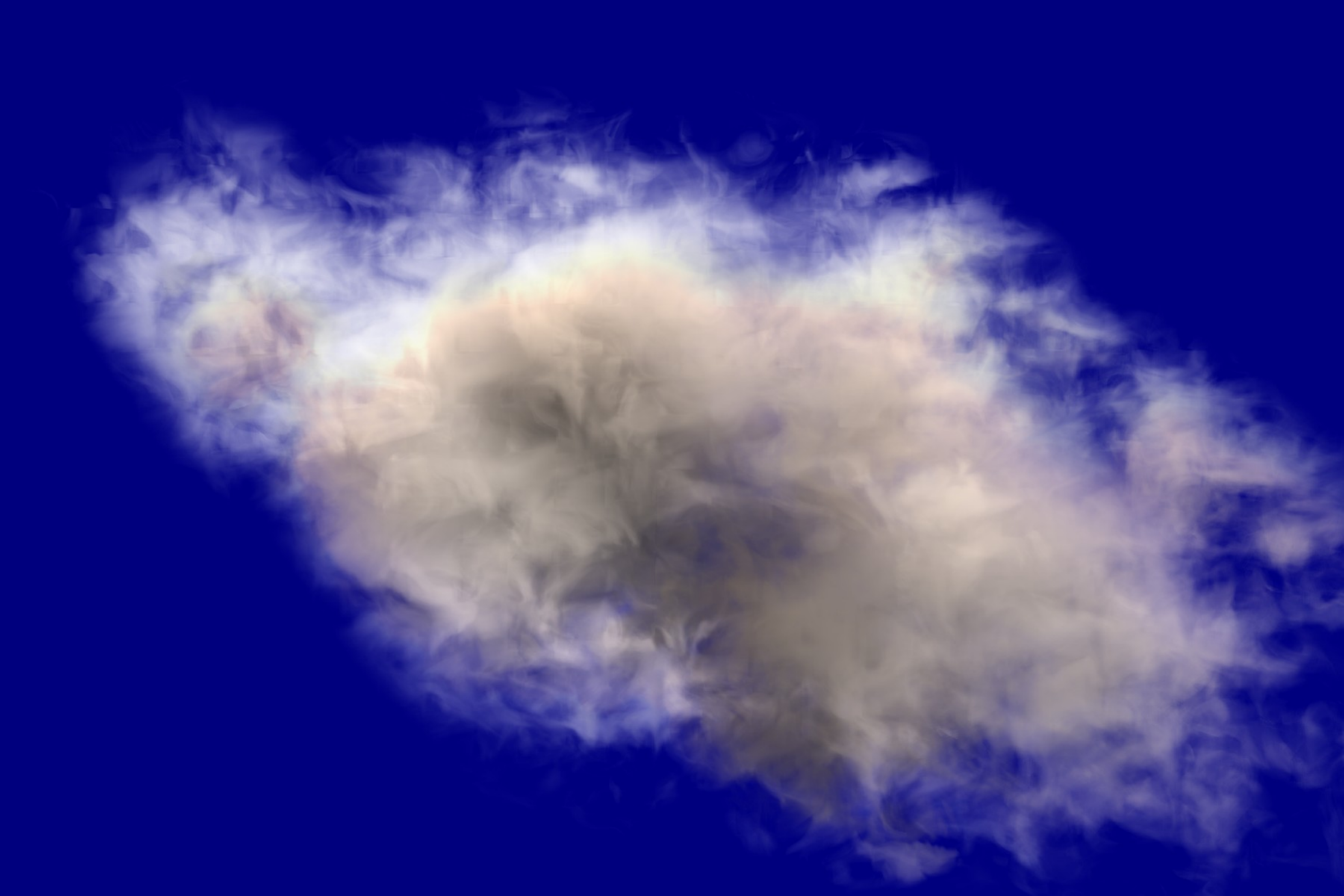
Simple Volumetric Procedural Model (VPM)

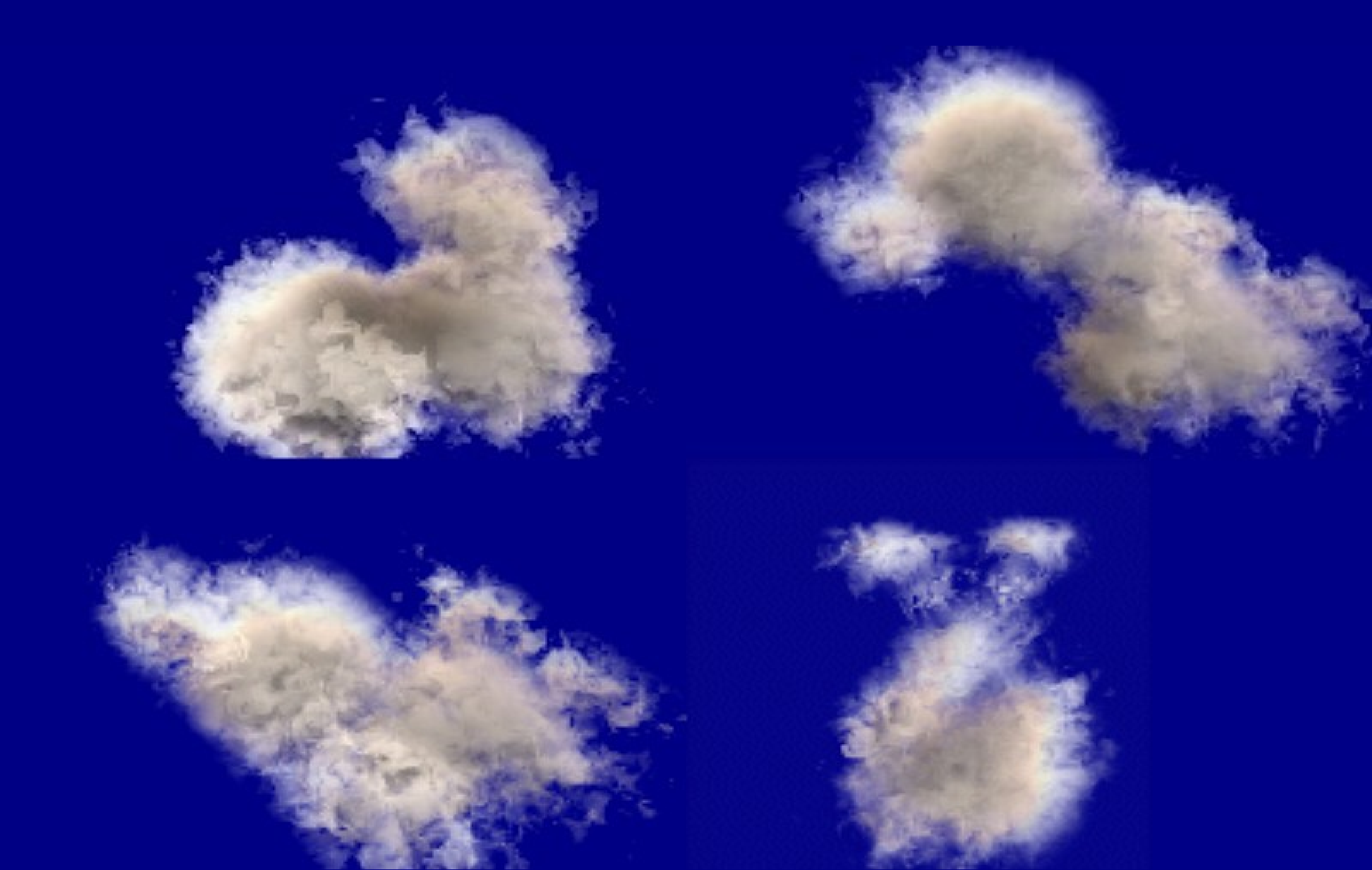
vpm(pnt)

- pnt = map pnt to procedural turbulence space
- turb = turbulence (pnt)
- density = pow(denseness*turb, wispiness)
- return(density)

Combined Model

- *Use Procedural Techniques to Perturb Sample Point*
- *Calculate Implicit Density for Point*
- *Calculate Procedural Density for Point*
- *Blend These Densities*
  - blend = blend% * imp_density + (1-blend%)*proc_density*imp_density
- *Shape With Math Functions*





Stratus And Cirrus Cloud Effects

Stratus Clouds

- Use a few implicits to specify extent of layer
- Use procedural techniques for details
- Denser and less wispy

Cirrus Clouds

- Use implicits for each cloud or for global shape
- Thinner, less dense, wispier

Another Example (Henrik Wann Jensen)

Procedural Cloud Model Based on the Techniques Presented

- Generates a large number of points describing cloud density

Realistic Cloud and Environmental Illumination Using Photon Maps

Animation: Little Fluffy Clouds

- Cloud density is increased procedurally
- Sun rises, cloud layer forms, sun sets

Examples Using Commercial Systems: A/W Maya

Rendering:

- Volumetric cloud plug-in

Animation

- Cloud formation dynamics in MEL

Volumetric Cloud Plug-in

(Marlin Rowley, Vlad Korolev, David Ebert)

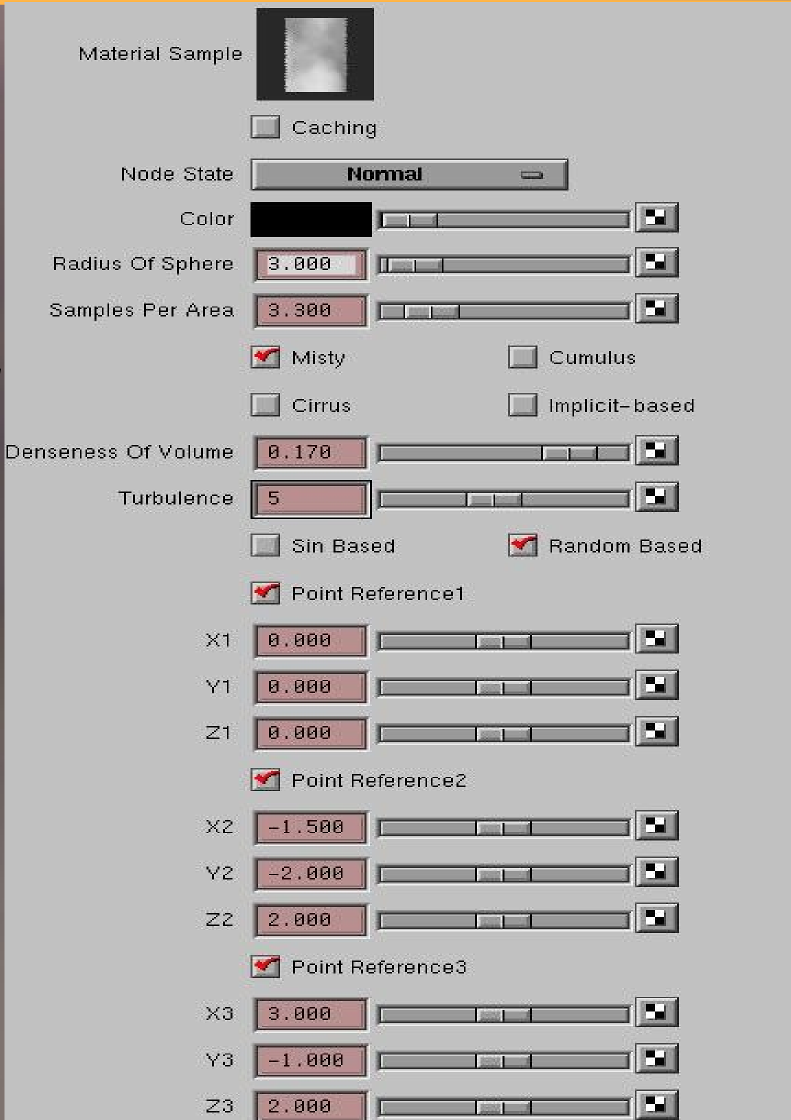
Prototype Volume Rendering Plug-in

Attached to Volume Light Shape

Cloud Shape: 3 Spherical Primitives

4 Cloud Types:

- Misty
- Cumulus
- Cirrus
- Implicit



Volumetric Cloud Plug-in: Examples

Plug-in Available

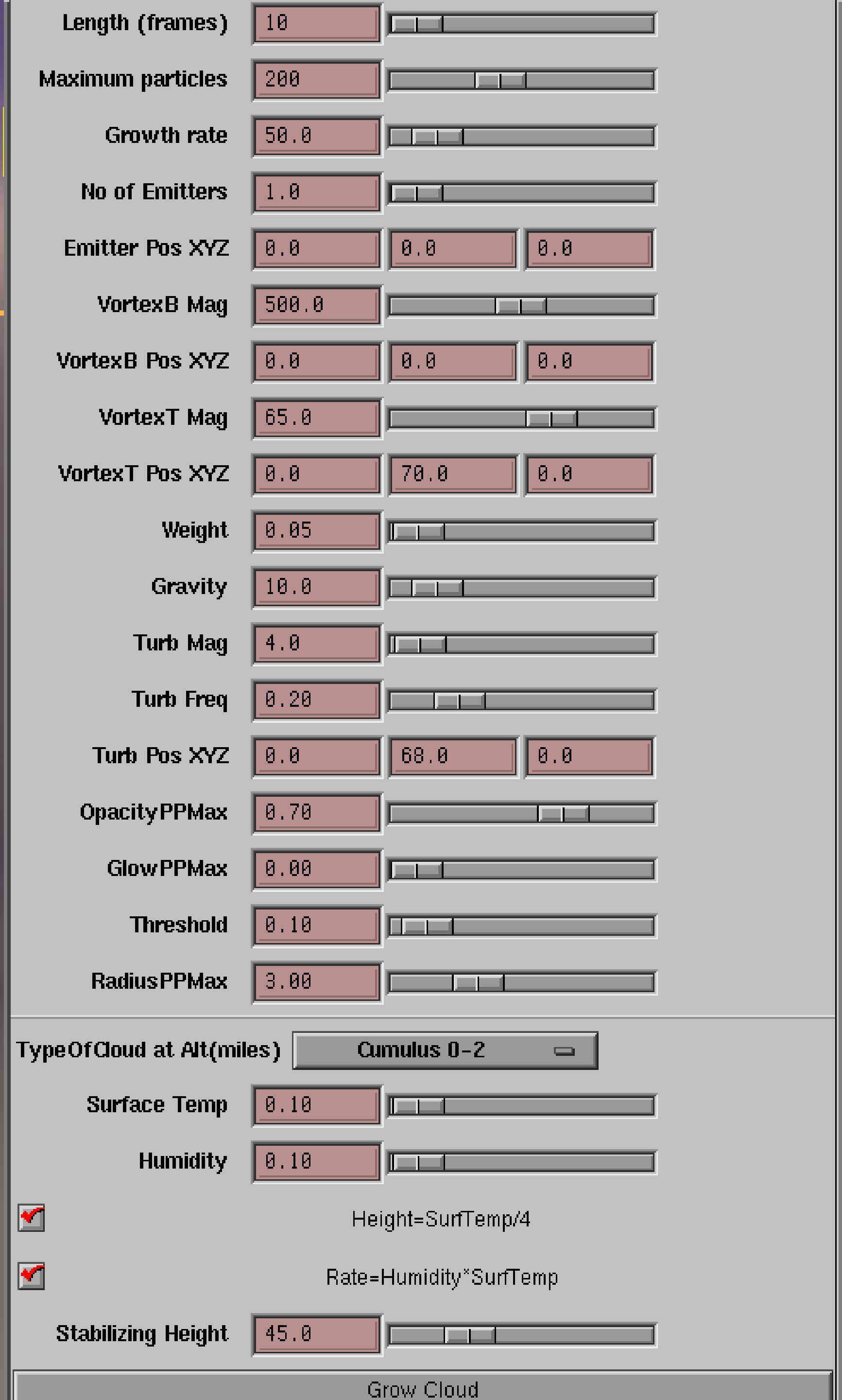
- **High End 3D web site rendering (rendering section)**
- **www.highend3d**
- **v3 for NT released 5/31/2001**

Cloud Dynamics in ME
(Ruchigartha)

Specialized Particle System

Dynamics Simulates

- Buoyant bubbles
- Temperature gradients - controls velocity
- Vortices
- Gravity
- Wind fields



Cloud Dynamics in MEL: Simulation

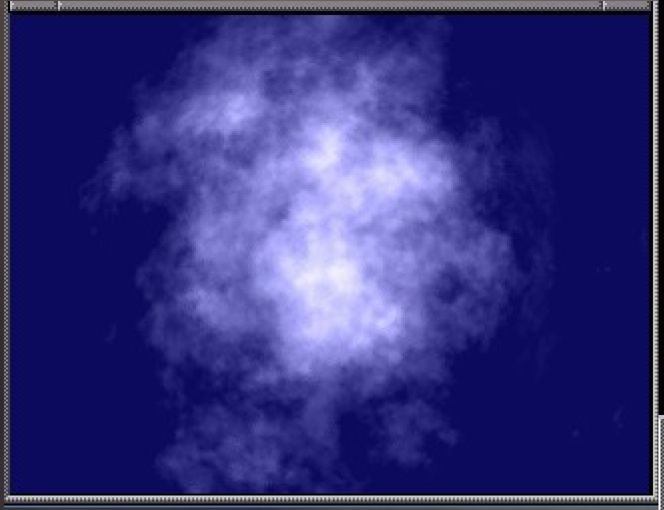
Particle Emitter

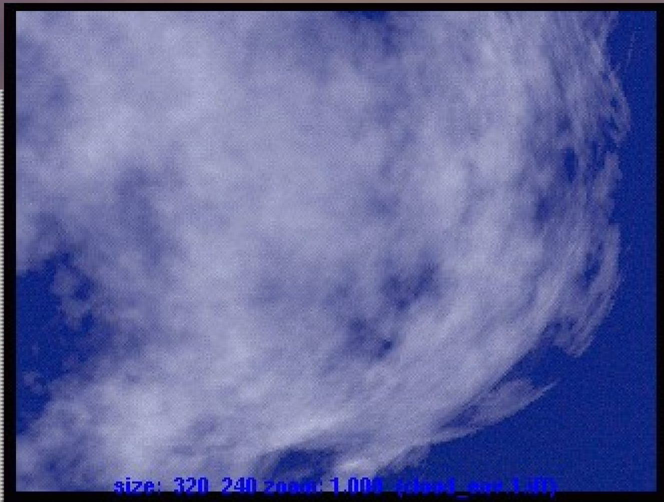
- Numerous settable attributes

Evaluate Forces on Particles

Create Children - Split Particles

Particle Death – Stabilize





Real-time Dense Gases: Issues

- *Volume Rendering vs. Approximations*
- *Static vs. Dynamic Models*
- *Semi-transparent Volume Accumulation*
- *Illumination*
- *Shadowing*

Issues for Real-time Gases: Volume Approximations

Particle Systems – Only Practical for Thin Gases

- No inter-particle illumination, shadowing
- Often simple transparency model (or none) – depth sorted?
- Probabilistic shading and shadowing can be used

Imposters / Billboards – Good for Distant Clouds

- For close-ups and fly-throughs must integrate cloud slabs onto imposter
  - *Very time consuming – slows performance*
  - *Use pre-computed tables to improve performance*

Issues for Real-Time Gases: Volume Approximations (cont.)

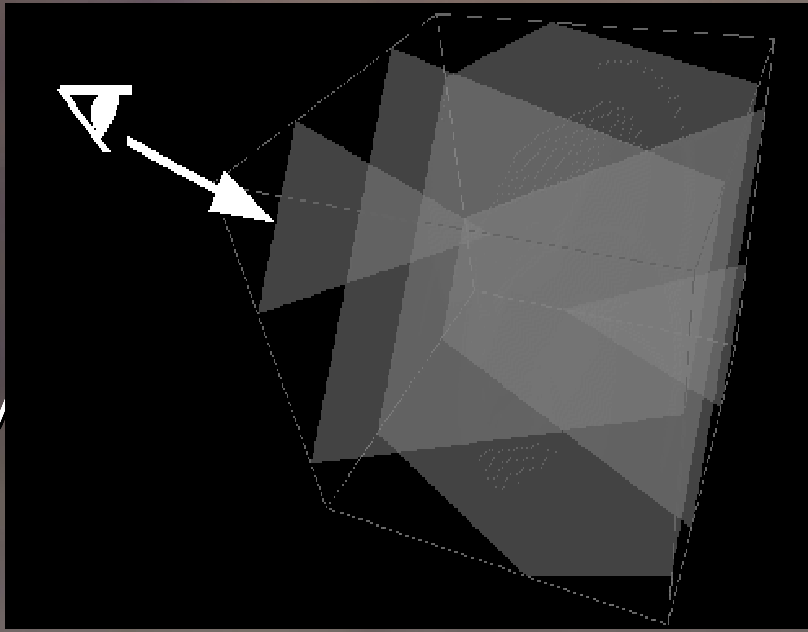
Textured Ellipsoids – Good for Distant Clouds

- Problem 1: need to handle view dependent illumination and shadowing
- Problem 2: fly-throughs
  - *must integrate cloud onto plane that slices through ellipsoid*
    - Need to update each frame
  - *Very time consuming – slows performance*
  - *Use pre-computed tables to improve performance*

Issues for Real-time Gases: Volume Rendering (Overview)

Hardware Approaches to Real-Time Volume Rendering

- Mitsubishi VolumePro board (>$5000)
- 3D texture mapping hardware
  - *Nvidia GeForce3, ATI Radeon (< $400)*
  - *SGI Octane, Onyx, … (>$10,000)*
- Limited resolution based on board memory
  - *256^3 (64Mb)?*



Interactive Software Solutions

- Splatting – Comes closest but is still seconds / frame

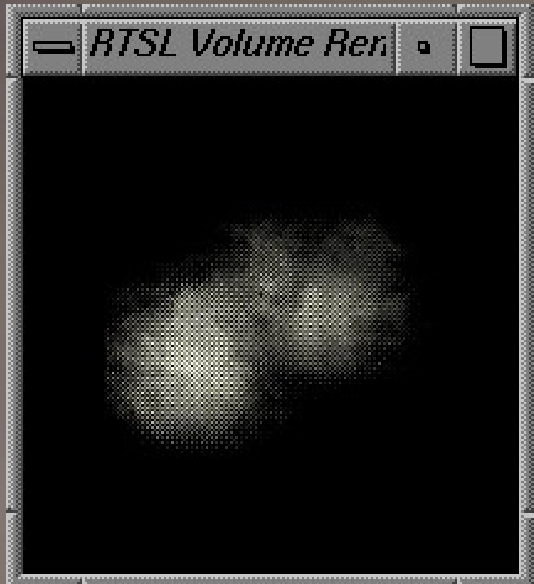
Issues for Volumetric Gases: Static Modeling

3D Textures for Gas Density

- Limited by resolution of 3D texture: 256^3 (64Mb)
  - *Not a very detailed cloud, want 1000^3 at least*
  - *What about shadow volume, illumination volumes, etc. => even more memory*
- Precision of densities / opacities: Is 8 bits enough?

Global Density Model + Volume Detail Texture (Noise Texture)

- Need dependent texture reads



Issues for Real-time Volumetric Gases: Dynamic Models

Dynamically Change 3D Texture Densities

- Need ability to update portions of 3D textures at 30 fps

Change 3D Texture Indices Algorithmically

- How quick can you change the texture coordinates on the slices?

Use a Changing Smaller Texture to Dynamically Offset the 3D Texture Lookup

Could Generate Geometry on the Fly (Micropolygons)

- Need capability to generate new triangles at the vertex or fragment processing level
  - *E.g. from a vertex program on a Nvidia chip*

Can use dummy geometry – but no textures in v.p.

Issues for Real-time Volumetric Gases: Opacity Accumulation

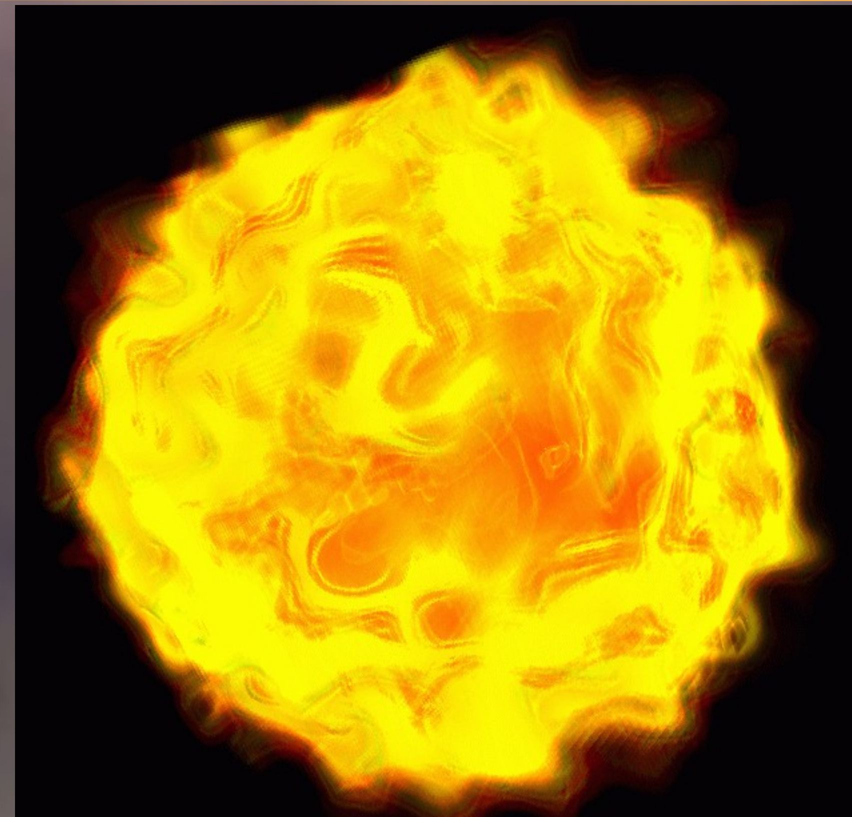
Need Exponential Accumulation of Gas Densities:

$$e^{-\tau \int_{t1}^{t2} density(\lambda)\, d\lambda}$$

- Most systems use simple linear blend

Can Pre-integrate Accumulated Opacity Within a Slab and Store That in the Texture (e.g., Engel 2001)

- Opacities at front and back plus step size become texture coordinates
- Requires dependent texture read



Courtesy of Klaus Engel, Pre-Integrated Volume Renderer V1.7, 15 fps, 2001

Issues for Real-time Volumetric Gases: Illumination

How to Simulate Bi-directional Reflection Function for Low-albedo Illumination

- 2D texture maps indexed by eye angle and light angle?
  - *Needs dependent texture read*

How to Simulate Multiple (High-albedo) Scattering?

- Could use pre-integrated tables
  - *Need to change for each move in observer position or light position*

Approximation of Isotropic Particle Scattering

- Only dependent on light direction

Issues for Real-time Volumetric Gases: Shadowing

How to Compute Real-time Shadows?

- 2D real-time shadow mapping
  - *Only would works for shadowing onto objects, not self-shadowing*
  - *Problem with transparent objects*
- Could create 3D shadow table using texture sliced renderer from direction of eye point
  - *Cuts frame rate approximately 25-50% depending on accuracy desired*
- Projected imposters to form shadow texture (Dobashi 2000)

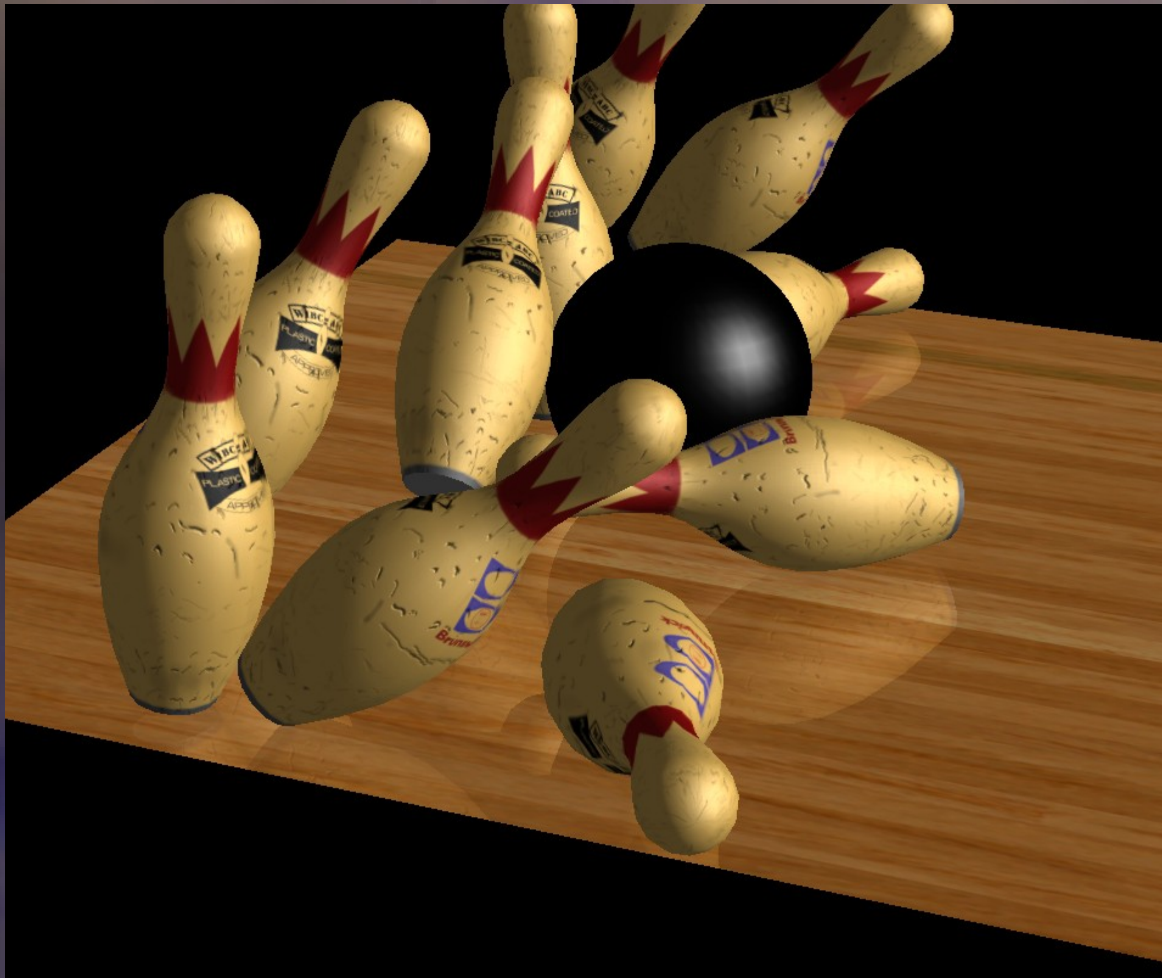
What's Now Available for PC Graphics?

- *3D Textures - (e.g., ATI, 3dfx, Nvidia, X-box)*
- *Programmable Vertex Shading (e.g., GeForce2, GeForce3)*
- *Dependent Texture Reads (e.g., ATI Radeon, GeForce3)*
- *Programmable Pixel Shading (e.g., GeForce3)*

What’s Now Available for PC Graphics?

Stanford Real-Time Programmable Shading Language (Mark, Proudfoot, Hanrahan)

- Great for real-time programmable shader development and volume shading design
- Re-targetable compiler to optimize passes through graphics pipeline
- Between OpenGL and Renderman



Hardware Issues With New Advances

How Much Flexibility in the New Programmability?

- Can you add, subtract, multiply, divide?
- Are conditionals allowed?
- How big is the temporary storage?
  - *Can you do noise tables?*
- Can you use 3D textures just like 2D textures in dependent reads?
- Any order of operations imposed by the hardware (implementation gotcha)?
- What operations are allowed in each part of the pipeline?

Hardware Issues With New Advances (cont.)

What Is the Range of the Values for Each Operation?

- 0 to 255, -255 to 255, fixed point, float

What Is the Precision?

- 8-bit, 9-bit, 12 bit, 16 bit?
  - *Affects complexity of operations that can be performed before quantization errors are visible*
- How does the precision vary at different stages of pipeline?
  - *E.g., Geforce 3 pixel shaders are floating point, but textures are 8-bit and combiners are 9-bit*

Conclusion

Procedural Modeling and Animation is :

Powerful

Flexible

Extensible

Conclusion

Important Aspects

- Flexible volume modeling system
- Accurate illumination and shadowing

Procedural Modeling

- Particle systems, L-systems, blobs can be included
- Flexible, turbulent volume modeling

Conclusion

Volumetric Procedural Implicit Cloud Modeling

- Ease of control and specification of implicits
- Smooth blending
- Natural appearance from turbulence simulation
- Procedural abstraction
- Parametric control

Conclusion

Real-time Gases Are On the Horizon

- Latest programmability and capabilities of PC hardware enables a vast array of techniques
- Procedural techniques are well suited for new hardware
  - *Eliminate the data transfer bottleneck*

Future Goal

- Download procedural cloud to GPU and generate geometry and render on the fly

Acknowledgements

Collaborators:

- RTSL: Bill Mark, Kekoa Proudfoot, Pat Hanrahan
- Klaus Engel, Rick Parent, Steve May
- Students: Marlin Rowley, Vlad Korolev, Ruchigartha

Funding: NSF, NASA, DoD, Electronic Arts